Big Sky Workshop on Super-Intense Laser-Atom Physics

June 22-25, 1991
Big Sky Lodge, Big Sky, Montana

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The workshop on super-intense laser-atom physics consisted of 22 invited talks and 32 presentations in the poster session.

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This Report includes ...

Big Sky Workshop on Super-Intense Laser-Atom Physics
Final Program

Saturday, June 22nd

Buffet Supper 6:30 – 8:30 p.m.

Beer, Wine and Cheese 8:00 – 9:00 p.m.

Evening Session — Marv Mittleman, Presider

9:00 Gavrila, "Floquet theory for super intense field ionization rates and atomic stabilization"

9:30 Eberly, "Space-time dynamics of atomic electrons in strong and super-strong fields"

10:00 Knight, "Interference stabilization of excited-state electrons"

Sunday, June 23rd

Breakfast 7:00 – 8:30 a.m.

Morning Session — Rick Jensen, Presider

8:30 Burnett, "Model atoms in super-intense fields: The Kramers-Henneberger picture"

8:55 Shakeshaft, "Numerical integration of the time-dependent Schrödinger equation"

9:20 Kulander, "Effects of pulse shape on the high frequency stabilization of hydrogen"

9:45 Tang, "Dynamics of 1-dimensional model and 3-dimensional hydrogen in an intense, high frequency, short pulse laser"

10:10 – 10:45 Coffee Break

10:45 Rzazewski, "Stabilization of atoms in strong laser fields: Classical approach" (long talk)

11:30 Sundaram, "Scarring and stabilization in super-intense laser fields"

11:55 Nefedov, "The classical atom in a strong laser field"

Lunch 12:30 p.m.

Supper 6:30 – 8:00 p.m.

Evening Session — Tom McIlrath, Presider

8:00 Melissinos, "Interaction of very high energy electrons with intense laser beams"

8:45 Freeman, "Generation of high intensity, high frequency light for use in super-intense laser-atom physics"

9:10 Artemyev, "Calculation of ponderomotive forces acting on a relativistic electron in the field of a strongly focussed laser pulse"

9:35 Mainfray, "Laser-matter interaction at 10^{18} W/cm^2"

Monday, June 24th

Breakfast 7:00 – 8:30 a.m.

Morning Session — Volodya Krainov, Presider

8:30 Pont, "Multiphoton ionization of atomic hydrogen in superintense, high-frequency laser fields"

8:55 Stroud, "Wave packets, trapping and classical orbits"

9:20 Delone, "The Stark atom"

9:45 Koch, "Microwave ionization of excited hydrogen atoms: Experiments with widely varying parameters"

10:10 – 10:45 Coffee Break

10:45 Krstic, "Atomic 'stabilization' in a high intensity laser field beyond the one mode and dipole approximation" (long talk)

11:30 Su, "ATI spectra in short-pulse intense laser fields"

11:55 Reiss, "Stabilization in the strong-field approximation"

Lunch 12:30

Supper 6:30 – 8:00 p.m.

Evening Session — Posters 8:00 p.m.

Tuesday, June 25th

Breakfast 7:00 – 8:30 a.m.

Morning Session — Tom Gallagher, Presider

8:30 Fedorov, "Interference of transitions from Rydberg levels to the continuum and suppression of ionization in a strong laser field"

8:55 Maquet, "Dynamics of harmonic generation by simple laser-driven anharmonic systems"

9:20 Faisal, "Line narrowing in the H-atom in an intense laser field"

9:55 Welge, to be announced

10:20 – 10:45 Coffee Break

10:45 Grobe, "Numerical experiments on electron-atom scattering in strong and super-strong fields" (long talk)

11:30 Bucksbaum, "Stabilization of Rydberg atoms in intense laser pulses"

Lunch 12:30 p.m.

Invited Talks

Model atoms in super-intense fields: The Kramers Henneberger Picture (1)

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We shall present some of our recent work on the behaviour of model-1-D atoms in super-intense fields. We have performed integrations of the time-dependent Schrödinger Equation in the Kramers Henneberger (KH) frame[1] (also called the acceleration gauge by some authors). This method offers significant advantages for computation as we shall show. This has enabled us[2,3,4] to perform a wide range of calculations with a modest amount of CPU time on a medium scale vector processor (The convex at Oxford University Computer Centre). Latterly we have adapted the code to run on our own small (5) transputer array making parameter surveys easier to perform. The advantages of the KH frame also extend to calculations for 2-D codes and realistic pulse lengths. So far we have studied photoelectron and harmonic generation for the model systems over a rather wide parameter range. These studies include harmonic generation at around ionisation over the barrier conditions. We have also examined the formation of extra dynamical features ie rainbows in long pulses (0.3ps) photoelectron spectra[3].

Ref

1. M Gavrila, J Z Kaminski Phys Rev Lett 52, 613 (1984)
   and Q Su, J H Eberly and J Javanainen Phys Rev Lett 64, 862 (1990)

2. V C Reed and K Burnett Phys Rev A 42, 3152 (1990)

3. V C Reed and K Burnett Phys Rev A in press.

4. K Burnett, P L Knight, B R M Piraux and V C Reed Phys Rev Lett 66, 301 (1991).

This work is part of a programme at Oxford University and Imperial College, London, supported by the United Kingdom Science and Engineering Research Council.

Numerical Integration of the Time-Dependent Schrödinger Equation

Bernard Piraux
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Marcel Pont, Daniel Proulx, and Robin Shakeshaft
Physics Department,
University of Southern California,
Los Angeles, California 90089-0484

We have developed two different approaches to the solution of the time-dependent Schrödinger equation for an atom irradiated by a short pulse. Calculations of ionization yields for atomic hydrogen can easily be carried out on a workstation using either method, at least for modest pulse durations (e.g. fifty cycles or so) and modest intensities (e.g. of order 10^{15} W/cm^2 for a frequency of 0.2 a.u., or larger intensities if the frequency is larger). The first method is based on using the split-operator technique. The full Hamiltonian is split into the atomic Hamiltonian and the atom-field interaction, and these two parts are diagonalized (once and for all) on a *complex* Sturmian basis. The numerical integration involves only a single matrix-vector multiplication per time-step, and when the symmetries of the evolution operator are exploited, the number of operations is reduced further. Storage requirements are not excessive (most of the calculations we carried out required no more than about 1 Mb, often less). The second method is based on solving the integral form of the time-dependent Schrödinger equation, again on a Sturmian basis. In this method the simple form of the evolution operator for the bare atom is exploited. The method is extremely rapid (as long as the intensity is not too large) since high accuracy can be achieved using few time-steps. For example, in the case of atomic hydrogen irradiated by a field of frequency 1 a.u., peak intensity 10^{16} W/cm^2, and temporal full-width at half-maximum of 5 cycles (total duration 20 cycles), the total number of time-steps needed to obtain 3 digits of accuracy is only about two thousand. We will present results for both one-color and two-color ionization, and we will illustrate a number of effects, including prominent stabilization of atomic hydrogen (against ionization).

This work was supported by the National Science Foundation under Grant No. PHY-9017079.

Effects of Pulse Shape on the High Frequency Sabilization of Hydrogen*

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Livermore, CA 94550

The ionization rate of an hydrogen atom subject to an super-intense, very short pulse, high frequency laser has been investigated by numerical integration of the time-dependent Schrodinger equation. Results for a photon energy of 1 a.u. (27.21 eV) have been obtained for a variety of pulse shapes with rise times from one to twenty optical cycles. A significant fraction of the initial wave function can be trapped in a relatively stable state as long as the pulse passes through the intensity window approximately bounded by 5×10^{15} and 2×10^{16} W/cm^2 in a few cycles. The structure of the stabilized state and its subsequent ionization dynamics is established during the passage through this window.

*This work was performed under the auspices of the U.S. Department of Energy at Lawrence Livermore National Laboratory under contract number W-7405-Eng-48.

Dynamics of 1-dimensional model and 3-dimensional hydrogen in an intense, high frequency, short pulse laser

X. Tang and S.Basile
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Los Angeles, CA 90089-0484

We present non-perturbative calculations of ionizing and trapping probabilities for 1-dimensional model and 3-dimensional hydrogen atom in an intense, high frequency, Gaussian pulsed laser field. Investigating the dynamics of the ionization process (for one and two photon ionization), we find that only for extremely short pulses laser with $\omega = 1$ a.u., especially for hydrogen, has the the system has a significant probability of surviving at the end of the pulse leading to the phenomenon of atomic stabilization with respect to ionization. We also find that a 1-dimensional model has a higher survival probability at the end of a Gussian pulse. as compared to the 3-dimensional hygrogen. We will also discuss the possibility of stabilization of the hydrogen from exited states with short pulse laser.

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Stabilization of Atoms in Strong Laser Fields Classical Approach

M. Gajda, J. Grochmalicki, M. Lewenstein
and K. Rzazewski

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Aleja Lotnikow 32/46, 02-668 Warsaw, Poland

We present the theory of stabilization of atoms in ultra strong laser fields based on classical approach. Employing the phase space averaging method and Monte Carlo techniques we show that stabilization effect that was discovered in the quantum framework, has its classical counterpart. We show that classical stabilization depends strongly on the dimension of the system, and is much harder to achieve in 3 dimensional atoms. We present detailed results concerning the probability of ionization, shapes and forms of electronic distribution functions. We discuss the role of pulse area effects, switching-on and -off times, as well as the interplay between the motion of a free electron in the laser pulse and in the presence of Coulomb potential.

Scarring and stabilization in super-intense laser fields

Bala Sundaram

Los Alamos National Lab.

ABSTRACT

The interaction of a model atom with super-intense fields [1] is approximated by a map which describes a free particle being kicked periodically by a double-well potential. [2] Comparisons of the quantum map with the solutions of the time-dependent Schrödinger equation indicates that the map provides a very efficient and accurate model for studying the high field stabilization of this strongly perturbed quantum system. In particular, we show that the "stabilized" wavefunction [1] results from the diabatic excitation of the eigenstates of the periodic, time-evolution operator (quasienergy states) localized near classically unstable and weakly stable orbits. The excitation of these "scarred" wavefunctions correctly accounts for the spacing of the peaks in the electron probability observed in numerical simulations. [1,3] These stabilized wavefunctions correspond to localized wavepackets that oscillate back and forth in the strong external field in the neighbourhood of the attractive Coulomb field. As a consequence, we show that the harmonic generation arising from the periodic bremstrahlung, as this wavepacket passes the nuclues, provides a distinct experimental signature for these stabilized states.

1) Q.Su, J.H.Eberly and J.Javanainen, Phys.Rev.Lett. 64, 862 (1990).

2) R.V.Jensen and B.Sundaram, Phys.Rev.Lett. 65, 1964 (1990).

3) Bala Sundaram and R.V.Jensen, in preparation.

The Classical Atom in a Strong Laser Field

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INTERACTION OF VERY HIGH ENERGY ELECTRONS WITH INTENSE LASER BEAMS

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The "Schwinger" critical field strength is defined as

$$E_c = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{11} \quad \text{V/cm}$$

We are currently using short (1 ps) laser pulses amplified to deliver 1 J of energy in the infrared ($\lambda = 1.054\mu$m). When this 1 TW pulse is focussed to near the diffraction limit, the resulting electric field is

$$E = 3 \times 10^{11} \text{V/cm}$$

Furthermore, if this pulse is incident on electrons of energy $\epsilon = \gamma m_e$, the field seen in the electron's rest frame is $E' = \gamma E$ so that for electrons of energy 50 GeV

$$E' = 3 \times 10^{16} \text{V/cm} \quad \sim 2E_c$$

The LEP storage ring at CERN and the SLC collider at Stanford routinely accelerate electrons/positrons to this energy and thus make it possible to reach critical field in laser-electron collisions.

The critical field strength can also be reached in other processes:

(a) Channeling of high energy electrons through thin crystals. These experiments have been performed at CERN and indicate a very large increase of pair production over the Bethe-Heitler formula.

(b) Relativistic heavy ion collisions. Experiments have been performed at GSI/Darmstadt and reavealed an unexplained peak in the e^+e^- mass spectrum.

(c) Beamstrahlung, i.e. the collision of very tightly focussed (transverse dimensions are of order of Angstroms) high energy electron-positron beams.

Finally intense laser beams scattered off high energy electrons can be used to produce beams of polarized multi-GeV gamma rays. A quantitative assessment of this possibility using the Stanford Linear Collider (SLC) will also be discussed.

GENERATION OF HIGH INTENSITY, HIGH FREQUENCY LIGHT FOR USE IN SUPER INTENSE LASER-ATOM PHYSICS

by

R.R. Freeman
AT&T BELL LABS
HOLMDEL, NJ USA

ABSTRACT

This talk will review the new methods for the production of high intensity, high frequency light for use in Super Intense Laser-Atom Physics experiments. We will concentrate on the production of light with photon energies greater than 100 eV, and intensities greater than $10^{13} W/cm^2$. Several areas of new technology will be emphasized: harmonic conversion of ultra-high powered visible lasers, the use of the new generation of undulators at the Advanced Light Source at Lawrence Berkeley Laboratories, and the use of newly-developed, diffraction-limited, high efficiency normal incidence mirrors for the refocusing of x-rays emitted from laser-induced plasmas.

The Accurate Calculation of Ponderomotive Forces Acting on a Relativistic Electron in a Field of a Strongly Focused Laser Pulse

Alexander Artemyev
General Physics Institute
Moscow USSR

Abstract:

The electron motion under the action of a strong space- and time-inhomogeneous electromagnetic wave is considered. The laser wave is represented as a superposition of plane waves. Such a description allows one to study accurately the ponderomotive forces acting on a relativistic electron in a field of a focused light wave for various polarizations of the wave, focal volume dimensions and laser pulse durations. In particular the applicability of traditional formulas describing the ponderomotive forces to the case of the electron motion in a field of a strongly focused ultra short laser pulse is discussed. It is shown that new expressions for the ponderomotive forces arise when an electron is affected by a strongly focused short laser pulse.

LASER-MATTER INTERACTION AT 10^{18} W/cm^2

G. Mainfray, L.A. Lompré, A. L'Huillier, T. Auguste,
P. Balcou, P. Monot and C. Manus

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Experiments on laser-matter interaction at 10^{18} - 10^{19} w/cm^2 are expected to dramatically improve our knowledge of fundamental aspects of this new area. The motion of electrons in the electromagnetic field at such intensities is relativistic, which is expected to lead to some interesting novel effects such as harmonic generation from electrons. Furthermore, the ponderomotive force is expected to lead to expulsion of energetic electrons from the focal volume, creating a dense cold plasma ideally suited for recombination and x-ray laser research.

A laser based on chirped-pulse amplification followed by temporal compression down to 1.1 psec delivers 1.5 TW at 1053 nm/1/ and a focused intensity up to 10^{18} w/cm^2 /2/. The laser pulse is focused onto a pulsed gas jet at a pressure which can be changed between 1 Torr and 1 atm. There is considerable stopping power in the focal region, with absorption of nearly all the pulse energy. Preliminary results will be presented.

/1/ M. Ferray, L.A. Lompré, O. Gobert, A. L'Huillier, G. Mainfray, C. Manus, A. Sanchez and A. Gomes. Opt. Commun. 75 278 (1990)

/2/ D. Normand, M. Ferray, L.A. Lompré, O. Gobert, A. L'Huillier and G. Mainfray, Opt. Lett. 15 1400 (1990)

Multiphoton ionization of atomic hydrogen in superintense, high-frequency laser fields

M. Pont

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April 8, 1991

Abstract

A review will be given about recent developments in multiphoton ionization (MPI) in superintense, high-frequency laser fields. Starting point is a by now fairly well-known high-frequency iteration scheme in increasing powers of the inverse frequency that was developed several years ago [1]. To lowest order in the frequency, i.e., the high-frequency limit, the atom was shown to be stable against decay by MPI, though distorted. In a frame of reference that oscillates along with a free electron driven by the laser field, the distorted states of the atom are stationary. To next order in the iteration, an expression for the MPI-amplitude was obtained. A brief summary of the general theory will be given and its physical consequences for the distortion of the hydrogen atom and its level shifts for the case of linearly polarized fields will be summarized [2].

Recently, we have made substantial progress by deriving an alternative form for the MPI-amplitude which is substantially simpler, though somewhat less accurate. Here we will be interested in the consequences of this simplified expression [3]. Special attention is paid to the case that the de Broglie wavelength of the photoelectrons is small with respect to the amplitude of oscillation of the (distorted) electronic cloud. This condition defines a radiation regime which yields features in sharp contrast to those obtained in weak fields. The *angular distributions* of photoelectrons are found to be characterized by rapid oscillations with the polar angle, arising from a peculiar way in which outgoing electron waves interfere. At the same time, the overall behavior of the photoelectrons is to be ejected in directions nearly perpendicular to the polarization axis. We have been able to solve analytically (under neglect of nonrelativistic effects) the limit of extremely high intensities at fixed, but otherwise arbitrarily chosen frequency analytically. We find that in 'ultrastrong fields' the *branching ratios* for decay by absorption of the various number of photons possible are only weakly dependent on the values of the intensity and frequency of the laser field, yet excess-photon ionization constitutes a sizeable part of the decay modes of the atom (typically 30%). At very high intensities, the hydrogen atom tends to stabilize at fixed, but otherwise arbitrarily chosen frequency. The (a priori unexpected) relative stability of the hydrogen atom in ultrastrong fields is explained as a result of 'radiative distortion' of the electron cloud and 'destructive interference' of outgoing electron waves. Although, the lifetime of the atom turns out to be extremely short for values of the intensity around the atomic unit, for low enough frequencies and very high intensities, it can be remarkably long. Finally, we discuss the problem of how the atom subject to these extreme radiation conditions could be observed experimentally.

References

[1] M. Gavrila and J.Z. Kaminski, Phys. Rev. Lett. **52**, 614 (1984). M. Gavrila, in *Atoms in unusual situations*, edited by J.P. Briand, NATO ASI Series B, Vol.143 (Plenum, New York, 1987), p.225.

[2] M. Pont, N. Walet, M. Gavrila and C.W. McCurdy, Phys. Rev. Lett. **61**, 939 (1988); M. Pont, N. Walet and M. Gavrila, Phys. Rev. A **41**, 477 (1990).

[3] M. Pont, *The Behavior of Atomic Hydrogen in Superintense, High-frequency Laser Fields*, Ph.D.-Thesis, Univ. of Amsterdam (unpublished, Feb. 1990). M. Pont and M. Gavrila, Phys. Rev. Lett. **65**, 2362 (1990). M. Pont, Phys. Rev. A, in press.

Wave Packets, Trapping, and Classical Orbits

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University of Rochester

Trapping of population in coherent superpositions of the ground state with low-lying levels of the same parity, and similar trapping among coherent superpositions of intermediate levels will be discussed and interpreted in terms of spatially-localized electron wave packets. These quantum predictions will be compared with purely classical simulations in which the individual realizations of the electron orbits can be followed.

The Stark Atom

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15

Microwave Ionization of Excited Hydrogen Atoms: Experiments with Widely Varying Parameters

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Derek Richards and Paul Dando
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Compared to tightly bound thermal atoms illuminated by a focused pulsed laser beam, excited fast-beam hydrogen atoms exposed to a microwave electric field offers another way to explore super-intense laser-atom physics. Because hydrogen atoms are easily studied with the latter technique, such studies directly meet the focus of this Workshop on single-electron physics at very high radiative field strengths, as long as "very high" means exerting a force on the electron that is comparable to the initial Coulomb binding force. Because the hydrogen atoms are intitially laser-excited into a state with principal quantum number in the range n_0=24-90, one needs rather modest microwave electric amplitudes in laboratory units. (In this case the bound and driven electron motions are non-relativistic.) Typically we use cw microwave power of from microwatts to watts being dissipated in a cavity resonator with Q-value near 10^4 to produce microwave electric amplitudes between 10^0-10^3 V/cm. Microwave frequencies are usually in the range between a few to a few tens of GHz. Extensive comparisons between experiment and theory, both quantal and classical, reveal different regimes of dynamical behavior of the driven system according to the value of the scaled frequency, the ratio of the driving frequency and the initial atomic frequency (quantally the initial n-splitting, classically the initial Kepler frequency). In all ranges studied so far, ionization requires net absorption of from tens to hundreds of microwave photons.

This talk emphasizes new experimental-theoretical comparisons in two regimes: (i) Very low scaled frequencies, from 0.02 to about 0.05, in which the dominant ionization mechanism is shown to be dynamical tunneling through the slowly moving potential barrier caused by the superposition of the Coulomb and external electric fields. We emphasize the importance of actual tunneling, as opposed to "over-the-barrier" escape, which is a classically allowed ionization mechanism that has been used to estimate e.g., "appearance intensities" in pulsed laser ionization of tightly bound atoms. (ii) Scaled frequencies in the range between 1-2, in which the excitation/ionization dynamics reveals a rich mixture of quantal and classical effects. Experimental data for three different driving frequencies and ranges of initial n-values show the classical scaling of ionization features that are not found in classical simulations of the experiments. These results dramatically confirm a theoretical explanation of local stability near certain values of the scaled frequency (e.g., 1.3) caused by "scarred wavefunctions". It is interesting that even though one of the three sets of experimental data was obtained with a envelope function ("pulseshape") very different from the other two, all three showed the same local stability effect.

To test the theoretical idea of "stabilization" of atoms being driven by a super-intense radiation field, we are going to mount an experiment that will expose the excited hydrogen atoms to a pulse of microwaves that will turn on and off very quickly (ca. one field oscillation or less) and whose overall duration will be on the order of only 10^1 field oscillations. If preliminary results are available at the time of the Workshop, they will be presented.

Atomic "Stabilization" in a High Intensity Laser Field Beyond the One Mode and Dipole Approximation

Predrag S. Krstic

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It has been shown recently that, within the framework of the nonrelativistic dipole approximation, a one mode high frequency, high intensity laser produces metastable states of atomic hydrogen. The binding energy and state width decreases with the increase of the laser intensity and therefore the high frequency approximation becomes unnecessary.

Inclusion of the relativistic and multipole corrections into the problem shows the bounds of validity of the previous results. If the laser becomes very intense bound states still exist, but they completely change their character. Particularly, previously found scaling laws and atomic dichotomy are lost. Binding energy and wave functions depend not only on one parameter, , but also on the laser frequency,

The spin behavior in the metastable atom is also changed and shows strong dependency on the laser field polarization. Circular polarization produces a new spin interaction term which is significant for strong, though realizable laser fields.

Multimode effects on the binding energy of hydrogen are also investigated. A multimode laser with fixed mode amplitudes and random uncorrelated phases yield an additional reduction of the binding energy and in some cases eliminates it entirely.

ATI Spectra in Short-Pulse Intense Laser Fields

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Abstract: Little attention has been paid to the behavior of above-threshold photoelectron energy spectra obtained with very short-pulse lasers in the regime of laser frequencies and laser intensities associated with atomic stabilization. We have studied such spectra numerically and analytically and will report the results. We will show the dramatic effect on ATI spectra accompanying the transition from the weak-field regime through the strong-field to the super-strong-field regime.[1] As laser intensity is increased, giant AC Stark shifts (red shifts) of ATI peaks are predicted to become giant blue shifts. We will show that an explanation of all of these peak shifts can be based on Kramers-Henneberger eigen-energies, without additionally invoking the familiar "ponderomotive" threshold shift.

1. Q. Su and J.H. Eberly, Phys. Rev. A 43, 2474 (1991).

STABILIZATION IN THE STRONG-FIELD APPROXIMATION

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The SFA (strong-field approximation) is a method well-suited to exploration of the stabilization phenomenon. Its properties are reviewed briefly. It is designed to retain field dependence to the maximum extent possible, but it is often not realized that this Keldysh-like method largely preserves atomic properties. The only requirement is that the ponderomotive potential of the ionized electron in the laser field should be larger than the no-field atomic binding energy of the electron. Atomic properties are fully retained in the initial state. The stabilization phenomenon is in clear evidence in basic transition rates or their inverses (the atomic lifetimes). This is strongly exhibited for circular polarization of the laser, but it is clearly present with linear polarization as well. Comparison with the circular polarization, space-translation results of Pont and Gavrila[1] is direct, with an interesting outcome. For high frequencies, where the space-translation method is most applicable, the SFA and space-translation results are numerically almost identical. The only difference of significance is in the neighborhood of the lifetime minimum, where the SFA dips lower and shows some fluctuations. This close numerical agreement of the two methods carries on to intensities well below those for which reliability of the SFA can consistently be claimed. The SFA applies in a frequency regime too low for the space-translation method, and stabilization is found here as well, but with qualitative differences from the high intensity case. Linear polarization is treated with the SFA, again using a broad range of frequencies. This is computationally much more difficult than the circular polarization case, but newly developed calculational algorithms allow one to compute reliably right up to the relativistic domain. Again the stabilization phenomenon appears clearly, and at intensities very similar to those that occur with circular polarization. At field intensities above the lifetime minimum, qualitative behavior for the two polarization cases becomes very unlike. A major question which remains to be answered is whether the minimum in atomic lifetime shown in the basic transition rates will actually be perceived in experiments with laser pulses distributed over time and over three-dimensional space. The means exist to find this answer.

INTERFERENCE OF TRANSITIONS FROM RYDBERG LEVELS TO THE CONTINUUM AND SUPPRESSION OF IONIZATION IN A STRONG LASER FIELD.

M.V. FEDOROV

University of Rochester, Rochester, NY, USA

General Physics Institute, Academy of Sciences, Moscow, USSR

Photoionization of a Rydberg atom can be accompanied by a secondary coherent population of levels neighboring to the initially populated ones via the Raman-type or Λ-processes. Transitions to the continuum from such secondary coherently populated levels can interfere with each other resulting in a suppression of ionization or stabilization of the atom. This phenomenon can occur if the laser-atom interaction energy is larger than spacing between neighboring Rydberg levels, i.e. if the field is sufficiently strong. This energy of interaction can be roughly estimated as the ionization width of Rydberg levels found in the first order of the perturbation theory. The formulated condition determines a lower border of a range of laser intensities in which the interference stabilization can occur. An upper border of this range is achieved when the laser-atom interaction energy becomes as large as the Rydberg electron binding energy. Interference stabilization of population at Rydberg levels also can take place in the process of multiphoton ionization from the ground level, if this process is accompanied by a sufficiently efficient excitation of Rydberg levels. Such an excitation can be provided by dynamical multiphoton resonances between the ground and Rydberg levels which arise in a strong laser field owing to the Ac Stark shift of levels depending on time t via a slowly depending on t laser field strength amplitude.

Dynamics of Harmonic Generation by Simple Laser-driven Anharmonic Systems

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We report on our investigations of several aspects of harmonic spectra generated by simple anharmonic systems, in the presence of a strong external laser field. We have considered various classical systems, among which the 3D hydrogen atom and 1D anharmonic oscillators, namely the cubic and quartic (Duffing). Several general features of harmonic generation emerge from this simple analysis, which allows to qualitatively reproduce the spectra from the Fourier analysis of the corresponding time-dependent dipole.

This study provides, in particular, interesting informations on the origin and extension of the plateau, which is present in the harmonic intensity distribution in terms of their order. It suggests, in fact, that the existence of the plateau is linked to the survival of characteristic "atomic" frequencies, a point which is confirmed by a study of the response of a (quantum) 2-level system.

Another point which emerges from our calculations is the fact that harmonic generation and multiphoton ionization, which both take place in the same laser intensity range, are competing processes. More precisely, our model clearly indicates that when the system is ionized, harmonics are no longer generated by the asymptotically free ejected electron.

Finally, we will report on our study of the time dependence of harmonic generation, through a wavelet analysis of the time-dependent atomic dipole, driven by a laser pulse. Our results indicate that the intensities of different harmonics can vary significantly in time and more generally depend, in turn, on the ionisation of the system.

LINE NARROWING IN H-ATOM IN INTENSE LASER FIELD

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We report on the results of calculations of the ionization life-time of hydrogen atom in an intense laser field by solving the radiative close coupling equations in the space-translated frame of reference. The same system of equations has been investigated by us [1] for the associated problem of electron scattering in a Coulomb potential subjected to an intense laser field. For the present purpose they are solved applying the ionization boundary conditions for the channel functions. Our results show different eases of live-narrowing or greater stability of the atom in different frequency and intensity domains. Thus,

(a) for high frequency ($\lambda = 80nm$) intense field showed the approach to a "stability threshold" near $I \sim 10^{17} w/cm^2$ and

(b) we also observed an interesting phenomenon of "local stability" of the atom for frequencies smaller than the ionization limit. Such a stability is associated with a region of increasing life-time with increasing intensity over a finite range; further increase of intensity beyond this range is found to destroy the stability. Thus, for example, with an wave length $\lambda = 193nm$, one such region of "local stability" is found to arise between $10^{13} - 10^{14} w/cm^2$.

Implications of these and related findings by other workers will be discussed.

Reference:

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Numerical experiments on electron-atom scattering in strong and super-strong fields+

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We have solved Schrödinger's equation numerically to obtain the time-dependent wave functions for an electron in strong and super-strong radiation fields while it undergoes a collision with a one-dimensional one-electron atom.

The spectrum of the light coherently generated in such a scattering event contains high-order odd and even harmonics. We investigate an interesting regime in which the partial capture of the incoming electron wave packet and the creation of a negative ion accompanies harmonic generation.[1]

In the case of a very high intensity laser field the negative ion stabilizes; i.e., the detachment rate counter-intuitively decreases with increasing laser intensity. The super-strong-field dynamics of an electron in a short-range potential are similar in most respects to those of an electron in a long-range Coulomb potential, and the amount of trapped population in the ground state can be comparably large.[2] We will compare the required laser frequencies as well as field strengths for an appreciable amount of stabilization in a negative ion system and a neutral atom. We will illustrate that scattering experiments can help to investigate the stabilization regime for negative ions. We will comment on the very close relationship between scattering and photodetachment in super-strong fields.

+ Research partially supported by the US National Science Foundation

* Feodor Lynen Fellow, A. von Humboldt Foundation.

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STABILIZATION OF RYDBERG ATOMS IN INTENSE LASER PULSES

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The stability of hydrogen in intense fields suggested by Pont and Gavrila occurs in the limit of "infinite" frequency (hnu >> Ry), and high intensity (wiggle amplitude a >> 1 Bohr)[ref 1]. They show that at high enough intensity, the atomic wavefunction splits into two parts, each localized far from the center of the system. Since electrons located far from the ion core are essentially free, and cannot exchange momentum with the nucleus, they therefore cannot absorb light, and so become stable against photoionization.

The Pont-Gavrila limits are not very feasible conditions in which to perform experiments, requiring vuv lasers in the 10**17 W/sq.cm. range. Furthermore, stabilized states still might not occur, due to the much higher ionization probability at lower intensites: The atoms in the sample will simply ionize as the laser turns on.

We suggest that Rydberg atom targets may overcome both of these problems. Rydberg states might not seem an obvious choice, particularly since in the accelerating Kramers reference frame where most of the calculations are performed, these large radius states may not show the dramatic wave-function splitting of ground state hydrogen. However, recent calculations indicate that the correct criterion for stabilization is not the relative size of the atomic radius compared to the wiggle amplitude, but rather the wiggle amplitude compared to h/p, the final state electron deBroglie wavelength [ref 2]. Furthermore, since Rydberg states have small overlap with the ion core, it may be possible to stabilize them despite the rising laser pulse. Finally, since they are only loosely bound, the very high frequency limit for them may be in the range of optical lasers. We will describe several stabilization scenerios, involving both Rydberg stationary states and Rydberg wavepackets.

References

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2. M. Pont, Invited talk at QELS'91, Baltimore, May12-17, 1991.

Posters

Integration of the Schrödinger Equation on a Massively Parallel Processor

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We have used a massively parallel computer, the Connection Machine (CM-2), to integrate the time-dependent Schrödinger equation for hydrogen in a radiation field. The equations have been solved both in the length and velocity gauges, and using both cylindrical-coordinate and partial-wave expansions of the wavefunctions. Particular attention has been paid to developing accurate methods of time integration. We have developed and evaluated two complementary methods of time integration. The first method sums the propagator to high order in a Taylor's Series. When the time-step length and the order of the Taylor series are adjusted simultaneously to yield the most efficient algorithm, the order of the Taylor series is typically in the range 16 to 32. The second method is an approach proposed by Richardson[1], which gives a unitary propagator that is particularly appropriate for the special architecture of the Connection Machine.

We have studied the ATI electron spectra, and high harmonic generation in atomic hydrogen at a variety of intensities and frequencies. We typically integrate the equations of motion over about ten optical periods. The field is ramped on linearly over 3.0 periods and ramped off in the same way. Harmonic-radiation spectra are determined from Fourier transforms of the time-dependent expectation value of the acceleration; photoelectron energy distributions are calculated by projecting the computed wavefunction onto continuum Coulomb wavefunctions after the field has been ramped off. With the laser frequency at $\lambda = 608$ nm the intensities used ranged from 1.6×10^{13} Wcm^{-2} to 4.4×10^{14} Wcm^{-2}. With laser frequency at 1/3 the Rydberg frequency, intensities used ranged from 5.0×10^{13} Wcm^{-2} to 2.0×10^{15} Wcm^{-2}. In each case the peaks in the photoelectron spectra are shifted to lower energies by an amount that is equal to the frequency shift of the ground state of hydrogen, as predicted by lowest order (non-vanishing) perturbation theory.

1) J. L. Richardson, "Numerical solutions to the time-dependent Schrödinger equation, Thinking Machines, Inc. preprint (1990).

QUANTITATIVE THEORETICAL PREDICTIONS FOR IONIZATION EXPERIMENTS IN VERY STRONG FIELDS

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A uniform goal in physics is to have theories which are capable of providing agreement with experimental observations, and being predictive of measurements not yet made. This has proven difficult in strong field ionization. The SFA (strong-field approximation) is designed to be useful at laser intensities such that the ponderomotive potential of the ionized electron in the field is greater than the binding energy of the electron in the undisturbed atom. Published measurements to date which satisfy this condition are those using a CO_2 laser, such as the results of Corkum et al.[1], and the extensive results of Augst et al.[2] from Rochester. It is already known that the SFA matches[1,3] the Corkum et al. results well. Comparisons are presented between the SFA theory and the Rochester data for single ionization of all the noble gases from helium to xenon, and a few cases of two-fold ionization. Important in these comparisons are the use of realistic time and space profiles for the laser pulse (provided by the experimentalists[2,4]), realistic atomic wave functions to employ in the theory, and calculational algorithms for the theory which provide accurate results under all circumstances. These last two items have been missing in earlier efforts, which have either used Keldysh theory, appropriate only for 1s hydrogen and limited in intensity applicability[5], or else the SFA used with wave functions designed for the negative ion problem. It is found from present calculations that significant "structure" exists in the results, which may be identified with apparent slope discontinuities in the data. Within the experimental uncertainties in absolute intensity measurements and in detector efficiency, it appears that agreement is quite satisfactory, using a theory with no ansatzen and no adjustable parameters. Second ionization results are of the correct order of magnitude using true rate equation solutions, which is computationally demanding with the detailed theory. Further strong-field experiments would be very desirable.

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P3

STRONG-FIELD FUNDAMENTALS: CONTACT TRANSFORMATIONS AND THE GOLDEN RULE

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Practical application of strong-field theories designed to be used beyond the radius of convergence of perturbation theory is quite recent. There is always a risk, when entering a novel environment, that one may use procedures thought to be entirely fundamental, but which are actually subject to limitations that are not immediately in evidence. An example is the use of contact transformations in quantum mechanics, where phase factors which are functions only of time can be extracted from a transition matrix element, and then become physically irrelevant when the absolute square of the matrix element is formed. The square of the matrix element is the quantity required for entry into the Fermi golden rule, and contact transformations can provide useful simplifications. This procedure breaks down in the presence of strong fields. Even when pure Floquet behavior exists (that is, for monochromatic fields), an important generalization of the golden rule must be employed[1]. The situation is even more complicated without the monochromatic limitation, and the consequences of an uncritical application of contact transformations and the golden rule can be major.

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An Overview of Time-Dependent Propagation Applied to Intense Field Dynamics

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Several recently developed techniques for the numerical solution of the nonrelativistic Schrodinger equation are described and applied to two one-dimensional model potentials which simulate intense laser field-atom interactions. The numerical techniques use a pseudo-spectral decomposition for the spatial operators with different choices for the time propagation. The most efficient of these time propagation schemes are found to be variants of Krylov subspace reductions. In addition to the high accuracy afforded by these methods, variable time-stepping can be introduced which has obvious advantages in the low-frequency limit. The properties of these methods are discussed in general and they are also applied specifically to two model potentials: the inverted Gaussian well, originally proposed by Bardsley and co-workers, and the "soft Coulomb" potential introduced by Eberly and co-workers. The important issues of accuracy and dependence on laser field envelope functions will be addressed.

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Timedependent Solution of the Schrödinger Equation for a Atomic Multichannel Problem

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We have solved the onedimensional timedependent Schrödinger Equation for a multichannel potential in the presence of an intense laser field. The multichannel potential describes an atomic system with multiple ionization thresholds corresponding to excitation of an ion core. The offdiagonal parts of the potential couple the various channels (configuration interaction). Our model atom, therefore, shows perturbed Rydberg series and autoionization. This allows us to study in a simple model problem the effects of configuration interaction on strong field multiphoton ionization.

Numerical Simulation of 2D Model Atom Ionization under Short Laser Pulses. LI YOU, JAN MOSTOWSKI AND JOHN COOPER, *Joint Institute for Laboratory Astrophysics, Boulder, Colorado.*—Many new features of atomic ionization in super strong fields have been discovered recently. Of particular interest is the question of ionization suppression, its physical origin and interpretation. The suppression of ionization, or stabilization, was discovered in numerical simulations and was attributed to the "dichotomy," i.e. splitting of the binding potential due to the interaction with super strong oscillating electromagnetic field. Stabilization has not yet been found in real physical systems, existing analyses are restricted to simplified models. Some of the studies[1-3] suggest that the effect is of universal nature. Other[4] claim that the effect is large in one-dimensional(1D) models only and becomes negligibly small in three dimensions because of the angular momentum of the electron. In order to elucidate the role of the number of dimensions in the process of ionization in ultra-strong fields we have undertaken a study of ionization of a model atom in one and two dimensions(2D). In both cases the atom is modelled by a particle in a short range potential[5]. The oscillating laser field is modelled by a pulse[6], the pulse duration T is equal to 10 optical cycles. We solve the Schrödinger equation in such field. The results of one dimensional calculations are compared with similar ones for a long range potential, no qualitative differences are found. Also comparison of the one dimensional and two dimensional simulations is given and the role of angular momentum in suppression of ionization is discussed.

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[5]$V(r) = -U_0 cosh^{-2}(r/a)$, where r denotes the spatial coordinate (1D) or the radial coordinate (2D).

[6]$E(t) = E_0 sin^2(\frac{\pi t}{2T}) sin(\omega t)$.

P7

INTENSE-FIELD PHENOMENA AND SHORT-RANGE POTENTIALS

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A three-dimensional δ-function short-range potential allows one to get as close as possible to an analytical solution for a bound electron in the presence of an electromagnetic plane wave of arbitrary intensity. Typically, quantities of interest such as total ionization rates or rates of harmonic production can be reduced to one-dimensional integrals. Owing to the three-dimensionality of the model, the effects of the polarization of the plane-wave field can be studied. The model provides a good description of negative ions, the applicability to atoms is debatable.

A review is given of results pertaining to multiphoton electron detachment and production of very high harmonics and their interrelations. The total detachment rate as well as the electron energy distributions are strongly dependent on the polarization. Particularly interesting polarization-dependent features are observed in two-color photodetachment. All of these effects can be traced back to the Wigner threshold law. The harmonic spectrum as a function of the binding energy or the intensity exhibits a good deal of structure. Individual harmonics may be suppressed by orders of magnitude. Channel closings in the ATI spectrum can be related to sudden spikes in the harmonic spectrum, while no such

effect is seen on the remaining ATI peaks. All of the effects that can be attributed to channel closings are eliminated if the spectra are plotted for the case where the binding energy plus the ponderomotive energy is kept constant. For low intensities, the results corroborate the validity of "modified perturbation theory". For higher intensities additional structure is left whose physical origin is unclear.

P8

Spectral Properties in Two–Color Above Threshold Ionization

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Results are reported for a model of a hydrogenic atom[1]. The clectrons are excited into the continuum by energetic photons from the ionization laser and simultaneously redistributed among the continuum states using a second laser, whose photons are much less energetic. This scheme separates peak switching, due to nonperturbative population redistribution, from peak suppression, which is cause by the ponderomotive shift of the ionization threshold.

The results are sensitive to the angular momenta of the bound state and of the laser fields. The angular distribution of the electron energies, the photoelectron energy spectra, bound–state population trapping, and the photon spectra are reported. The solutions include laser pulse shape and delay – time effects and the rotating – wave approximation is avoided.

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P9

Classical Treatment of a Kicked Particle in One and Three Dimensions

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We present a numerical analysis of the ionization in superintense laser pulses based on a classical model. The ionization rate corresponds to the percentage of unbound particles of a cloud modelling the quantum mechanical electron cloud. The sinusoidal form of the external laser field is substituted by an alternating series of kicks. For realistic values of the frequency, pulse duration, turn-on and turn-off time one obtains stabilization for superintense external fields not only in the one dimensional but also in the three dimensional model.

For the one dimensional model the analysis of the stroboscopic plots shows, that the phase space area of classically regular motion increases with the field strength in the superintense regime. If one always looks immediately after a kick, the center of this regular area is displaced more and more in momentum for increasing field strength. Therefore, in order to obtain stabilization, the turn-on has to push the initial cloud away from the origin into the regular area; conversely, the turn-off must bring back these particles near to the origin.

As the regular area is not displaced in real space it is easier to decide whether stabilization has occurred or not when looking at the real space distribution of the classical particles instead of the energy distribution. This is demonstrated also for the three dimensional case.

Multiquanta Photodetachment from the H^- Ion*

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Multiphoton detachment (MPD) of an electron from the loosely bound H^- system (binding energy= 0.754 eV) has been studied at various photon energies and laser intensities. In the center of mass of 800-MeV H^- ions the CO_2 laser photon energy, 0.117 eV, was Doppler tuned over a wide range, from 0.15 to 0.39 eV. The peak laser intensity in the lab frame was varied from 2 to 12 GW/cm^2. The general behavior of MPD versus photon energy and the ac-Stark/ponderomotive effects are of special interest in the study. Characteristic threshold structures by absorption of 2, 3, 4, and 5 photons were observed, as evidenced by rapid changes in the signal amplitudes. These thresholds provide a straightforward picture of channel opening in MPD as the photon energy is increased. A fit of two-photon detachment data to the Wigner threshold law showed a good match with a small intensity-induced shift in the threshold energy. A study of laser intensity effects demonstrated departures from the simple power law predicted by lowest-order perturbation theory, which is possibly another indication of ponderomotive shifts in the threshold. The absolute MPD rates have been estimated and found to be in fairly good agreement with the results of Floquet theory.

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Polarization and Intensity Effects on Multiphoton Detachment of H^- and H^0 *

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Using crossed laser-relativistic ion beam (800 MeV) techniques, we have measured 2 and 3-photon detachments of the 0.75 eV bound electron in H^- as a function of CO_2 laser polarization and intensity. Using Doppler tuning the 2- photon threshold region was scanned in photon energy with linear and circular laser polarization. The threshold rose much faster for linear polarization than for circular polarization. The data fit closely to the Wigner threshold law for a short-range potential. Laser intensity scans were made at fixed photon energies of 0.391 eV and 0.330 eV. The results show good agreement with general power law dependence along with a effective "detuning" due to ponderomotive effects. Observations of 2-photon excitation from n=4 to n=11 in neutral hydrogen were also made.

* Supported in part by Div. of Chem. Sc., Office of Basic Energy Sc., Office of Energy Res., U.S. D.O.E.

Intensity Resolved Excess-Photon Ionisation in Noble Gasses

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Femtosecond pulses are eminently suited for electron-spectoscopic studies of high-intensity multiphoton ionisation. These pulses permit the determination of the light intensity at the exact moment of ionisation, because the intensity-dependent shift of the ionisation potential is no longer disguised by ponderomotive effects. Thus the intensity I is related to the shift of electron energy ΔE from its low intensity value as

$$\Delta E = \frac{e^2}{2m\omega^2 \varepsilon_o c} I$$

The ability to distinguish between ionisation events occuring at different intensities has led to the discovery of numerous resonances in seven-photon ionisation of xenon [Freeman et al, 1987]. Especially in combination with frequency tunable lasers the occurrence of resonances gives valuable information about Stark shifts of atomic levels at high intensities [Agostini et al, 1989]. In contrast to what second-order perturbative calculations predict, these studies revealed that almost all excited states tend to shift by an amount given by the ponderomotive shift.

In this study we report photo-electron energy spectra of some noble gasses over a range of laser wavelengths. At the intensities used, there is a significant amount of excess-photon ionisation (EPI). We are able to select the intensity at which the ionisation occurs by tuning the laser wavelength. Thus we are able to measure EPI spectra at one single intensity, without being hindered by the presence of a wide range of intensities in our laser focus. By following a specific resonance over a certain wavelength interval, the intensity, at which ionisation via this resonance occurs, can be varied continuously, keeping other relevant parameters as constant as possible. The relative rates of ionisation into different EPI channels thus can be measured accurately as a function of absolute intensity. The results are compared with theory.

The experiments are done with a magnetic bottle spectrometer, that automatically measures the angle-integrated ionisation rates. The resolution of our spectrometer is approximately matched by the inherent energy width of such a multiphoton process for pulses of this duration. In order to be able to cover a large range of intensities, the electron spectra are binned according to pulse energy. A pulse shaping device in our laser system allows us to set both bandwidth and central frequency of our light pulses.

Agostini P, Breger P, l'Huillier A, Muller H G, Petite G, Antonetti A and Migus A 1989 Phys. Rev. Lett. 63 2208

Freeman R R, Bucksbaum P H, Milchberg H, Darack S, Schumacher D and Geusic M E 1987, Phys. Rev. Lett. 59 1092

P13

Strong Optical Field Ionization of Gases in the Collisionless Regime *

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Using an intense, ultra-short laser pulses we are studying the rapid ionization of gases. To date ion yields have been observed. Our initial goals are to better understand the ultra-fast, strong optical field ionization process in a collisionless regime and to apply results to measuring peak laser pulse intensities using ion and photoelectron signals.

Our dye laser system currently provides 1 to 2 millijoules within 100 femtoseconds at a 10 pps repetition rate. We can then explore the dynamic regime in which peak electric fields rapidly approach the 10^9 Volts per centimeter level for near diffraction limited focusing (peak intensities near 10^{16} Watts /cm^2). Ionization rates can then exceed the optical frequency. This ultrafast character at visible photon energies (laser wavelength is 616 nm) affords a better distinction of a field ionization picture.

Using an f/5 off-axis-parabola the laser pulse energy is focused into the source region of a 1 meter time-of-flight tube. The ion charge states which survive the extinction of the laser pulse are temporally dispersed and detected with a dual microchannel plate device at the end of the tube. Operating in the pressure range, 10^{-7} to 10^{-5} torr eliminates collisional effects and counting rate limitations imposed by the detector. Plotted ion signal amplitudes for observed charge states show both the thresholds and ion balances to be sensitive functions of intensity.

For many cases studied peak fields are sufficiently high for tunneling ionization to occur (based on the values of the Keldysh parameter). Optical field ionization calculations integrated over a single pulse envelope are compared to our ion data. We are developing a more fundamental model to describe the effects of strong a.c. fields on bound systems. As the laser develops toward the designed 1 Joule per pulse, these investigations can be extended to peak intensities of order 10^{18} to 10^{19} Watts /cm^2. Rapid gaseous ionization experiments are relevant to the development of recombination based X-ray lasers for which a relatively 'cold' distribution of photoelectrons is expected.

* *This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.*

Tunnelling Regime of Ionization With Hg as an Experimental Evidence

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Abstract

Some "Keldysh-like" theories are analyzed leading to a practical definition of the tunnelling regime of ionization of atoms. Rather than using the more extreme definition for tunnelling (ie. $\gamma \ll 1$, $F \ll F_{at}$), a more precise definition of the Keldysh γ parameter ($\gamma < 0.5$) and of the laser field F ($F < F_{BSI}$) is proposed, where F_{BSI} is the barrier suppression ionization field. Recent experimental results of the ionization of mercury atoms by a CO_2 laser are presented. This experiment along with some previous experiments may be classified as tunnel ionization under this new definition.

P15

Relativistic Beams Control by Superintense Laser Light

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Abstract:

The interaction of relativistic electron beams with the superintense interference laser fields is investigated. The possibility of electron channeling, collimation and bunching is shown. The new methods of parametric conversion and harmonic generation are discussed.

P16

A search for the optimum geometry for electron acceleration by an intense laser with an improved magnetic field in a vacuum

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P17

Quantum and Classical Dynamics of Ground State Ionization by Intense Laser Fields

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Abstract

We have compared classical and quantum dynamics of high field intensity ionization as a function of system parameters for four distinct, standard, one-dimensional model systems. The potentials treated are the Duffing, Anharmonic, Hydrogen and Morse potentials. The results of the numerical experiments establish the evidence that the ionization probability, P , vanishes for large, potential dependent, Kramers parameter, $\alpha = A/\omega^2$, where A is the amplitude and ω is the frequency of the laser field. Results also show that suppression of P for large A in the quantum dynamics is potential-dependent. It is demonstrated that the mechanism of "gating" of the potential by the external field is instrumental in the classical picture of photoionization.

* Work performed for the U.S. Army Missile Command under Battelle Columbus Laboratories Contract DAAL03-86-D-0001. Permanent address: Department of Physics, University of Alabama in Huntsville, Huntsville, AL 35899.

Approximate Heisenberg Operator Calculation of Strong-Field Ionization and Harmonic Generation. Burke Ritchie and Britton Chang, LLNL. The Schroedinger equation is integrated in space and time to calculate the photoionization dynamics and harmonic generation in a generic one-dimensional model in a strong, monochromatic field. These results are compared against approximate Heisenberg operator calculations, and generally good agreement is obtained. Since the Heisenberg operator for the electron position is approximated by a classical trajectory, this result show how to use classical dynamics to simulate Schroedinger wave-packet dynamics. The average of the classical trajectories at each time step using the initial wave function is found to give a good approximation for the average of the Schroedinger electron position using the exact time-dependent wave function. The harmonic spectrum is calculated from this function. Results for the hydrogen atom will also be available for the conference. The calculation can be done in a fraction of the time required for a Schroedinger calculation. Also since the method depends on classical dynamics and an initial, stationary-state wave function, it should be useful to study the atom as a many-electron object rather than an independent-electron model.

Classical Mechanical Calculations for Harmonic Generation in Multi-Electron Atoms

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The role played by the inter-electronic forces in the generation of higher order frequencies in atoms by very strong optical fields in the ultra-short pulse regime is beginning to draw the attention of theorists[1] as well as experimentalists[2]. It has already been recognized that the inter-electronic forces can change the ionization of multi-electronic atoms by strong optical fields from a sequential mode to that of a collective mode. In harmonic generation, an electron can be thought of as a nonlinear oscillator which interacts with the field to produce higher order harmonics. If in the ultra-short pulse regime in which the inter-electronic forces can significantly alter the ionization dynamics of an atom, then it is reasonable to assume that the inter-electronic forces can also change the power spectrum for the harmonics generated by the atom. A change in the power spectrum occurs, because the inter-electronic forces couple the oscillators of the radiated power which are the electrons. The changes anticipated are for example: frequency shifts and new combination tones. These effects are known to occur when linear oscillators are coupled. Thus the inter-electronic forces are expected to have an analogous effect on the spectrum of radiated power from a multi-electronic atom. It is important to recognize that we may infer collective ionization from a change in the power spectrum, since the power spectrum is generated before the atom is ionized. We will use Ritchie's method[3] of approximating the Heisenberg operator with an ensemble of classical trajectories to calculate the dipole moments. Experimental effort is being made by Fittinghoff, et. al. to measure the distribution of charge states, and the measurement of the power spectrum are in its initial stages of planning. A comparison between theory and the data that is available at the time of the conference will be made.

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Optical Second-Harmonic Generation in Gases with a High-Intensity CO_2 Laser

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Abstract

Second-harmonic generation (SHG) is observed experimentally by using a tightly focused 2ns, 500mJ CO_2 laser pulse in a gas cell which contains helium, nitrogen and argon gases separately. The intensity ranges from 1.5×10^{12} to 6×10^{12} W/cm^2. Under the electric dipole approximation, SHG in centrosymmetric media is forbidden. The mechanism of SHG in our experiment can be explained as follows. After the formation of the plasma which is generated by the rising part of the laser pulse, the charges are separated by the ponderomotive potential. This charge separation then induces a static electric field which breaks down the inversion symmetry of the medium.

P21

Generation of Harmonic Radiation During Electron Scattering From a Piecewise Constant Potential In An Intense Electromagnetic Field*, R. A. Sacks and A. Szöke, *Lawrence Livermore National Laboratory, Livermore, California 94550.* In previous work[(1)], we presented and discussed an exact solution for the scattering of electrons by a piecewise constant potential in the presence of a strong electromagnetic field. An intimate connection with the physics of multiphoton ionization (MPI) was demonstrated. Here, we extend that work and present the first accurate evaluation of power radiated at harmonics of the applied field frequency during electron scattering from a potential in a strong electromagnetic field. The results are non-perturbative and manifestly gauge invariant. We observe the production of multiple order harmonics whose relative intensities as a function of harmonic number are similar to those of the above threshold ionization (ATI) peaks. No plateau in radiated intensity as a function of harmonic number is seen. Suppression of even harmonics in a symmetric potential is seen if the incoming state is strictly single parity (even or odd), but this suppression is found to be exceedingly sensitive to admixture of a small component of the opposite parity. In scattering from a well with two bound states, we observe a striking minimum in the third harmonic intensity for incident electron energy close to resonance.

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SPATIAL DISTRIBUTION OF HIGH ORDER HARMONICS GENERATED WITH A HIGH INTENSITY ND:GLASS LASER

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We have measured the spatial profiles of high-order odd harmonics (up to 31st in krypton) generated during the interaction of a 1-µm, 1-ps laser pulse with intensities between 10^{13} and 10^{16} W/cm^2 and noble gases. The existence of high order odd harmonics has previously been demonstrated using a 1 µm wavelength laser.[1]

The harmonics are emitted co-linearly with the laser beam and the profile of each harmonic is distributed in a cone shape similar to that of the incident laser. Our spectrometer is designed to measure the spatial distribution as well as the harmonic content of incident VUV light. Both measurements can be made on a single laser shot.

The presence of laser harmonics is first detected at approximately the same intensity as that which produces ionization of the medium. Under the high intensity laser conditions used here, the ionization of krypton occurs in the "tunneling" regime rather than the "multi-photon" regime.[2] The tunneling regime is entered when the oscillatory energy of electrons in the laser field is larger than half the ionization potential of the atom or ion.

We will discuss the spatial distribution and intensity dependence of the harmonics and the relation between harmonic and ion production and present an estimate for the harmonic production efficiency in this ionization regime.

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Ionization of Ground State and Excited Atoms in High Intensity Laser Fields

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Recent ionization experiments have demonstrated that the ionization of noble gas atoms with 1 ps, 1 μm laser light can be explained by a 1-D classical picture of Barrier Suppression Ionization(BSI).[1] Further experiments using circularly and linearly polarized light have shown the non-resonant nature of the ionization process under these laser conditions.

For initial atomic states in high Rydberg levels, quantum mechanical effects may lead to strong-field ionization suppression.[2] These previous calculations were performed for a constant laser intensity. We have extended them to include temporally and spatially dependent laser pulses. We find that for a temporally Gaussian laser pulse, the survival probability will be of order 50% when the laser pulse duration and peak laser intensity, I_0, satisfy

$$\frac{I_c}{I_0} \ll \omega_n \tau \leq \sqrt{\ln\left(\frac{I_0}{I_c}\right)},$$

where, ω_n is the orbital frequency of the n$^{\text{th}}$ Rydberg level, I_c is the intensity at which the ionization rate is predicted to begin to decrease with increasing laser intensity,

$$I_c = \frac{\omega^{10/3}}{\pi^2 c^2 Z^{2/3}},$$

and c is a factor of order 0.1.

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Quantum Localization and Stabilization of Rydberg Atoms in Very Intense, Very High-Frequency Radiative Fields

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Because Rydberg atoms have weaker binding energies and lower natural frequencies relative to ground atomic states, they form ideal systems for experimental tests of predictions of quantum localization of classical chaos, relevant for high frequency, moderately high intensity radiative fields, and stabilization of atoms, relevant at high frequencies and very high intensities. Two possible extensions to the theory of quantum localization of classical chaos to the case of very high frequencies are pursued, and results are presented for delocalization thresholds and ionization rates for a one-dimensional Rydberg atom in an intense laser field. It is shown that, for moderately high intensities above the delocalization limit, the chaotic ionization rate is linearly proportional to the intensity of the radiative field, but much higher than the single-photon ionization rate, a surprising result, because it has previously been assumed that single-photon ionization would dominate in this regime. Some results are also presented in the stabilization regime, in which the intensity of the radiative field is even higher, and it is shown that the stabilization effect is stronger for model atoms in which the Coulomb potential has been smoothed at the origin than it is using the true Coulomb potential.

P25

The stability of a model atom in a strong short laser pulse with a smooth envelope

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INHIBITION OF IONIZATION IN STRONG LASER FIELDS

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We analyze the excitation of atoms by intense pulsed laser fields and describe a physical mechanism leading to a strong inhibition of atomic ionization. This inhibition of atomic ionization results from the formation, through the Raman Coupling, of a spatially extended wave packet.

In order to illustrate this mechanism, we consider the two-photon ionization of atomic hydrogen, initially in the 2s-state, by an intense ultra-short laser pulse. We show that the population in the low lying p-states is gradually transferred to high lying p-Rydberg states through virtual transitions via the initial state, high lying Rydberg states and continuum states. The wave packet, formed relatively far away from the nucleus, interacts weakly with the field; in addition, because it involves many excited states, it is highly non-harmonic and spreads rapidly; this rapid spreading prevents the overlap with the nucleus from becoming large at any time. As a result, the ionization is strongly suppressed.

Our theoretical approach to describe the excitation dynamics of atomic hydrogen consists of expanding the total wave function on a large set of unperturbed states; we then numerically solve the corresponding system of first order equations for the amplitudes of probability. Results for the ionization yield, the electron energy spectrum and the time evolution of the populations will be presented.

P27 MODEL ATOMS IN SUPER-INTENSE FIELDS II: IONIZATION SUPPRESSION

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We examine the dynamics of atomic ionization in super-intense fields directly in terms of the Kramers-Henneberger frame [(1)] using appropriate eigenstates of the radiatively dressed atomic potential [(2)]. We show that atomic stabilization [(3)] is intimately dependent not only on intensity and frequency but also on pulse turn-on characteristics which determine the distribution of Kramers-Henneberger states which are excited. We directly demonstrate that for normal pulse rise-times, states other than the Kramers-Henneberger ground state are populated and that the general form of the stabilized electron wave packet is not dichotomous.

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P28

DYNAMIC STABILIZATION OF ATOMIC HYDROGEN IN A VERY HIGH FREQUENCY LASER FIELD WITHOUT DICHOTOMY OF THE WAVE FUNCTION

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ABSTRACT

We present numerical computations of three-dimensional atomic hydrogen ionized by a linearly polarized laser field. We consider square pulses of one atomic unit of intensity and different frequencies. We found that for a very high frequency field (10 a.u.) almost total stabilization appears. We have also seen that, in this limit, stabilization appears without dichotomy of the wave function.

PHOTO-IONIZATION OF THE HYDROGEN ATOM: THREE-DIMENSIONAL RESULTS AND PSEUDO ONE-DIMENSIONAL MODEL.

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ABSTRACT

Photo-ionization of atomic hydrogen by a linearly polarized laser is numerically studied using a method based on a expansion of the wave function in angular momentum components. The numerical method presented is quite efficient to compute photo-ionization of three-dimensional atoms. Moreover, the main advantage of the method is that allows a clear comparison with one-dimensional models. As a consequence, we propose a new family of models that have the same complexity than a one-dimensional model but that are closer to real atoms.

P30

Quantum dynamics of atomic hydrogen in super-intense, ultra-short laser pulses

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Abstract:

The stability of atoms in intense radiation fields is a subject of great current interest. Using a new multidimensional Discrete Variable Representation, we consider the quantum dynamics of atomic hydrogen subject to super-intense laser pulses. Results will be presented on issues of ionization suppression and stability and quantum interference phenomena.

P31

Multiphoton Ionization Rates for Atomic Hydrogen: Linear and Circular Polarization Compared

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An upgrade has been performed of our previously described method[1] of calculating the photoionization rate for a hydrogen atom interacting with an intense laser field. The predictor-corrector algorithm for solving, in the time domain, the spatially discretized form of the corresponding time-dependent Schrodinger equation has been replaced by the more efficient Bulirsch-Stoer method[2]. Reductions of up to a factor of three in the required computer time have been encountered.

Calculations of the photoionization rate for atomic hydrogen, reported earlier[3], have been repeated and improved using this new algorithm. Significant decreases in the rate have appeared, at laser irradiances below $10^{15} W/cm^2$, for a photon energy of 5 eV. The reasons for this decrease will be discussed.

Good agreement now exists between the results of our calculations, and those of three other groups[4–6], for the photoionization rate of atomic hydrogen, initially in its ground state, when interacting with the 5 eV photons of a linearly polarized laser beam, over a range of irradiances $10^{13} - 10^{15} W/cm^2$. These results are still in apparent disagreement with recently reported experimental measurements of these rates[7], as well as with the detailed predictions of the Keldysh-Reiss formulas[8,9].

An extension of our calculations for laser circular polarization is also reported. Values of the photoionization rate for atomic hydrogen are determined for 5 eV photons at several laser irradiances, and comparison is made with the results obtained for linear polarization, and with the predictions of refs. 8 and 9.

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RESONANT MULTIPHOTON EXCITATION OF MOLECULAR VIBRATIONS BY INTENSE INFRARED LASER PULSES

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The anharmonicity of molecular vibrations has been the major obstacle to the multiphoton dissociation of a small molecule [1]. Even at laser intensity 10^{14} W/cm^2 the dissociation cannot compete[2] with considerable ionization occuring at such intensity. By contrast, our numerical simulations based on the time dependent Schrödinger equation describing the interaction of the Morse oscillator with laser radiation show[3] that appropriately chirped pulse yield 20% dissociation at intensity $I=10^{12}$ W/cm^2. In these calculations we used pulses whose frequency $\omega(t)$ decreases at a rate adapted to the molecular anharmonicity and satisfying the condition known from two-level system that the most efficient excitation is obtained when the pulse area is equal to π [4]. The dissociation probability thus obtained is many orders of magnitude higher than for a monochromatic pulse of the same intensity. Such pulses should be useful for more efficient multiphoton selective dissociation or excitation of molecular bonds of polyatomic molecules and thus creating quantum states inaccessible by thermal excitation[5].

We have calculated also[6] the power spectrum of the induced dipole moment by a monochromatic picosecond pulse near resonant with molecualar vibrations. We observed a considerable generation of higher harmonics as well as the power broadening of harmonic peaks at $I > 10^{12}$ W/cm^2. At laser intensities close to the dissociation threshold instead of usual harmonic generation one observes a strong generation of a discrete but dense spectrum. This manifestation of resonant nonperturbative effects can be viewed as a signature of a chaotic behaviour of the system.

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